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POSSIBLE $\Delta\Delta$ DIBARYONS IN THE QUARK CLUSTER MODEL [1]

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Abstract

In the framework of RGM, the binding energy of one channel $\Delta\Delta_{(3,0)}(d^*)$ and $\Delta\Delta_{(0,3)}$ are studied in the chiral $SU(3)$ quark cluster model. It is shown that the binding energies of the systems are a few tens of MeV. The behavior of the chiral field is also investigated by comparing the results with those in the $SU(2)$ and the extended $SU(2)$ chiral quark models. It is found that the symmetry property of the $\Delta\Delta$ system makes the contribution of the relative kinetic energy operator between two clusters attractive. This is very beneficial for forming the bound dibaryon. Meanwhile the chiral-quark field coupling also plays a very important role on binding. The S-wave phase shifts and the corresponding scattering lengths of the systems are also given.

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1 Introduction

With the consideration that the Quantum Chromodynamics (QCD) is the underlying theory of the strong interaction, the hadronic systems are assumed to be composed of quarks and gluons, and most of descriptions of baryons are associated with some effective degrees of freedom of nonperturbative QCD (NPQCD), such as constituent quarks [1], and chiral fields [2], etc.. But, in the multi-baryon system, the property of the system mostly can be well explained in the baryon and meson degrees of freedom with only some special cases where the quark and gluon degrees of freedom has to be taken into account as exceptions[3]. In principle, nothing special would prohibit a system with the baryon number larger than one, and there might exist dibaryons which are composed of six quarks. Many efforts have been made in both theoretical and experimental investigations to search such object in past years [4-7]. Unlike the deuteron, the dibaryon has a QCD motivated origin and should be a system with quarks and gluons confining in a rather smaller volume, say smaller than 0.85fm in radius. In this system, both the perturbative QCD (PQCD) and the NPQCD effects should be taken into account. However, because of the complexity of NPQCD, one has to use effective models to simulate the strong interaction, especially in the NPQCD region. Thus, investigating dibaryons is a prospective field to test various models of NPQCD, and consequently, to enrich our knowledge of the QCD phenomenology.

According to Jaffe's calculation with the bag model [4], the color magnetic interaction (CMI) of the one-gluon-exchange (OGE) potential of the H particle is attractive. In 1987, K.Yazaki [8] investigated non-strange six-quark systems by considering OGE and confinement potentials and showed that CMI in the $\Delta\Delta_{(3,0)}$ system demonstrate the attractive feature among the NN, $N\Delta$ and $\Delta\Delta$ systems. Therefore, this state Is highly possible a dibaryon. Studying this system is particularly plausible.

Since Jaffe predicted the H dibaryon in 1977 [4], many works have been done on searching the possible existences of dibaryons such as strangenessless dibaryons d^* [5,8-10] and d' [11] and the strange dibaryons such as H, $\Omega\Omega$, $\Xi^*\Omega$ and $\Xi\Omega$ [13,14,12]. The current calculations of H showed that the mass of H is around the threshold of the $\Lambda\Lambda$ channel [14,15]. This result is consistent with the reports of current experiment [16]. The recent theoretical result of d^* is obtained by considering the coupling of the $\Delta\Delta$ and CC(hidden color) channels in the chiral quark models. It is shown that the binding energy of d^* is in the order of tens MeV [10]. The predicted $\Omega\Omega$, $\Xi^*\Omega$ and $\Xi\Omega$ are about 100 MeV, 80 MeV and 30 MeV, respectively[12, 23-25].

In the theoretical study of dibaryon, the quark cluster models have been Intensively employed. With these models, one can easily realize the antisymmetrization character between quarks belonging to different clusters, which can only be neglected when clusters are well separated from each other.

For the system with a radius not larger than 0.85fm, the Pauli principle on the quark level would play a substantial role [20]. According to our calculation, $\Delta\Delta_{(3,0)}$ (d^*) has the most antisymmetized property in the spin-flavor-color space, which is characterized by the expectation value of the antisymmetrizer in the spin-flavor-color space. This property appears in another non-strange six-quark system, $\Delta\Delta_{(0,3)}$. In this paper, we would discuss the one channel $\Delta\Delta_{(0,3)}$ together with d^* within the chiral quark cluster model. The paper is organized in such a way that the model is briefly presented in Sect.2, the results and discussions are given in Sect.3 and the conclusions is drawn in Sect.4.

2 The effective Hamiltonian and two-cluster wavefunction

As an effective theory of QCD, in the chiral quark model, the constituent quark and the chiral field are assumed as the effective degrees of freedom, and a long-range confinement term, which dominants the long-range NPQCD effect and still cannot strictly be derived up to now, a short-range one-gluon-exchange term, which describes the short-range QCD effect and a set of terms induced by the coupling between the quark and chiral fields, which mainly depict the short- and medium-range NPQCD effects are considered as the effective interaction. Thus the dynamics of a six-quark system in the SU(3) chiral quark model is governed by the effective Hamiltonian [18,19]

$$H \ = \ T \ + \ \sum_{i<j}(V_{ij}^{CONF} \ + \ V_{ij}^{OGE} \ + \ V_{ij}^{PS} \ + \ V_{ij}^{S}), \tag{1}$$

where T denotes the kinetic energy operator of the system and V_{ij}^{CONF}, V_{ij}^{OGE}, V_{ij}^{PS} and V_{ij}^{S} represent the confinement, one-gluon exchange, pseudo-scalar chiral field induced and scalar chiral field induced potentials intervening between the $i-$th and $j-$th quarks, respectively. The confinement potential can phenomenologically take a quadratic form

$$V_{ij}^{CONF} \ = \ -(\lambda_i^a\lambda_j^a)_c(a_{ij}^0 + a_{ij}r_{ij}^2), \tag{2}$$

where the superscript a is the color index. The OGE potential can be derived from the perturbative tree diagram

$$
\begin{aligned}
V_{ij}^{OGE} &= \frac{g_i g_j}{4}(\lambda_i^a \lambda_j^a)_c \, [\, \frac{1}{r_{ij}} && - \quad \frac{\pi}{2}(\frac{1}{m_i^2}+\frac{1}{m_j^2}+\frac{4}{3}\frac{\vec{\sigma}_i\cdot\vec{\sigma}_j}{m_i m_j})\delta(\vec{r}_{ij}) \\
& && - \quad \frac{1}{4m_i m_j r_{ij}^3} S_{ij} - \frac{3}{4m_i m_j r_{ij}^3}\vec{L}\cdot(\vec{\sigma}_i+\vec{\sigma}_j) \,],
\end{aligned} \tag{3}
$$

with the tensor operator S_{ij} being

$$
S_{ij} \quad = \quad 3(\vec{\sigma}_i\cdot\hat{r}_{ij})\,(\vec{\sigma}_j\cdot\hat{r}_{ij}) - (\vec{\sigma}_i\cdot\vec{\sigma}_j) \; . \tag{4}
$$

The pseudo-scalar and scalar field induced potentials are originated from the restoration of the important symmetry of strong interaction—the chiral symmetry and can be written as

$$
\begin{aligned}
V_{ij}^{PS} &= C(g_{ch},\ m_{\pi_a},\ \Lambda)\,\frac{m_{\pi_a}^2}{12 m_i m_j} \\
&\cdot \quad [f_1(m_{\pi_a},\ \Lambda,\ r_{ij})\,(\vec{\sigma}_i\cdot\vec{\sigma}_j) + f_2(m_{\pi_a},\ \Lambda,\ r_{ij})\,S_{ij}\,](\lambda_i^a\lambda_j^a)_f \; ,
\end{aligned} \tag{5}
$$

and

$$
\begin{aligned}
V_{ij}^{S} &= -C(g_{ch},\ m_{\sigma_a},\ \Lambda)\cdot[f_3(m_{\sigma_a},\ \Lambda,\ r_{ij}) \\
&+ \quad \frac{m_{\sigma_a}^2}{4m_i m_j}\,f_4(m_{\sigma_a},\ \Lambda,\ r_{ij})\,\vec{L}\cdot(\vec{\sigma}_i+\vec{\sigma}_j)\,](\lambda_i^a\lambda_j^a)_f \; ,
\end{aligned} \tag{6}
$$

respectively. In above equations, the subscript f denotes the flavor index. The functions f_i, Y, G, and H and the constant c-number C are

$$
f_1(m,\ \Lambda,\ r) \quad = \quad Y(mr) - \left(\frac{\Lambda}{m}\right)^3 Y(\Lambda r), \tag{7}
$$

$$
f_2(m,\ \Lambda,\ r) \quad = \quad H(mr) - \left(\frac{\Lambda}{m}\right)^3 H(\Lambda r), \tag{8}
$$

$$
f_3(m,\ \Lambda,\ r) \quad = \quad Y(mr) - \frac{\Lambda}{m}\,Y(\Lambda r), \tag{9}
$$

$$
f_4(m,\ \Lambda,\ r) \quad = \quad G(mr) - \left(\frac{\Lambda}{m}\right)^3 G(\Lambda r), \tag{10}
$$

$$
C(g,\ m,\ \Lambda) \quad = \quad \frac{g_{ch}^2}{4\pi}\,\frac{\Lambda^2\, m}{\Lambda^2 - m^2}, \tag{11}
$$

$$
\tag{12}
$$

respectively, with

$$
\begin{aligned}
Y(mr) &= \frac{1}{mr}\, e^{-mr}, & (13)\\
G(mr) &= \frac{1}{mr}\left(1+\frac{1}{mr}\right) Y(mr), & (14)\\
H(mr) &= \left(1+\frac{3}{mr}+\frac{3}{m^2r^2}\right) Y(mr), & (15)\\
\frac{g_{ch}^2}{4\pi} &= \frac{9}{25}\,\frac{g_{NN\pi}^2}{4\pi}\left(\frac{m_q}{M_N}\right)^2. & (16)
\end{aligned}
$$

In Eq.(5), π_a with ($a = 1, 2, ..., 8$, and 0) correspond to the pseudoscalar fields π, K, η_8 and η_0, respectively, and η and η' are the linear combinations of η_0 and η_8 with the mixing angle θ [14]. In Eq.(6), σ_a with ($a = 1, 2, ..., 8$, and 0) denotes the scalar fields σ', κ, ϵ and σ, respectively.

In the framework of Resonating Group Method (RGM), the wavefunction of the Six-quark system can be written as

$$\Psi_{6q} = \mathcal{A}[\Phi_A\Phi_B\chi(\mathbf{R}_{AB})Z(\mathbf{R}_{cm})] \tag{17}$$

where $\phi_{A(B)}$ denotes the wavefunction of cluster A(B), $\chi(\mathbf{R}_{AB})$ is the trial wavefunction between clusters A and B, $Z(\mathbf{R}_{cm})$ is the wavefunction of the center of mass motion (CM) of the six quark system and $\mathcal{A}$ represents the antisymmetrizer. Expanding the unknown wavefunction $\chi(\mathbf{R}_{AB})$ by well-defined basis functions, such as Gaussian functions, one can solve RGM bound state equation to obtain eigenvalues and corresponding wavefunctions, simultaneously. The details of solving RGM bound-state problem can be found in Refs. [21,22].

The model parameters should be fixed at the very beginning by the mass splittings among N,Δ, Σ and Ξ, respectively, and the stability conditions of octet ($S = 1/2$) and decuplet ($S = 3/2$) baryons, respectively. The resultant values are listed in Table 1.

Table 1 Model parameters under $SU(3)$ chiral quark model

	Set1	Set2		Set1	Set2
m_u (MeV)	313	313			
m_s (MeV)	470	470			
b_u (fm)	0.505	0.505			
m_π (fm^{-1})	0.7	0.7	Λ_π (fm^{-1})	4.2	4.2
m_k (fm^{-1})	2.51	2.51	Λ_k (fm^{-1})	4.2	4.2
m_η (fm^{-1})	2.78	2.78	Λ_η (fm^{-1})	5.0	5.0
$m_{\eta'}$ (fm^{-1})	4.85	4.85	$\Lambda_{\eta'}$ (fm^{-1})	5.0	5.0
m_σ (fm^{-1})	3.17	3.17	Λ_σ (fm^{-1})	4.2	7.0
$m_{\sigma'}$ (fm^{-1})	4.85	4.85	$\Lambda_{\sigma'}$ (fm^{-1})	5.0	5.0
m_κ (fm^{-1})	4.85	7.09	Λ_κ (fm^{-1})	5.0	7.61
m_ϵ (fm^{-1})	4.85	7.09	Λ_ϵ (fm^{-1})	5.0	7.61
g_u	0.936	0.936			
g_s	0.924	0.781			
a_{uu} (MeV/fm^2)	54.34	57.71	a^0_{uu} (MeV)	-47.69	-48.89
a_{us} (MeV/fm^2)	65.75	66.51	a^0_{us} (MeV)	-41.73	-50.57
a_{ss} (MeV/fm^2)	102.97	115.39	a^0_{ss} (MeV)	-45.04	-68.11

In this table, m_A denotes the mass of particle A which can be either valence quark or meson involved, Λ_A represents the corresponding cut-off mass of the particle, g_q is the coupling constant of gluon to the valence quark q, $a_{q_1q_2}$ depicts the confinement strength between valence quarks q_1 and q_2, respectively, and $a^0_{q_1q_2}$ denotes the corresponding zero-point energy. It should be mentioned again that with both sets of parameters, one can reasonably reproduce the NN and NY scattering data and part of single baryon properties and renders a mass of the H particle which agrees with the available experimental data [17-19,23-25].

3 Results and discussions

We are now ready to study the structure of $\Delta\Delta$ dibaryons. First of all, let us look at the symmetry character of the $\Delta\Delta$ system. As is emphasized above, the antisymmetrization of quarks belonging to different clusters plays a substantial role in the structure of the dibaryon. In both $\Delta\Delta_{(3,0)}$ and $\Delta\Delta_{(0,3)}$ systems, the expectation value of he antisymmetrizer in the spin-flavor-color space, $\langle\mathcal{A}^{sfc}\rangle$, is equal to 2. As a result, the kinetic energy term provides an attractive effect. Therefore, although the CMI of $\Delta\Delta_{(0,3)}$ does not have an attractive nature like $\Delta\Delta_{(3,0)}$, it is still possible to form bound $\Delta\Delta_{(0,3)}$ like $\Delta\Delta_{(3,0)}$.

With parameter Sets 1 and 2, we calculate the binding energy and the root-mean-square-radii (RMS) of two systems. The results are tabulated in Table 2.

It is shown that both $\Delta\Delta_{(3,0)}$ and $\Delta\Delta_{(0,3)}$ are bound states, their binding energies are a few tens of MeV and the correspondent RMS' are around 1 fm. The binding nature of $\Delta\Delta_{(0,3)}$ is consistent with our speculation. The binding energy of $\Delta\Delta_{(0,3)}$ is lower than that

of $\Delta\Delta_{(3,0)}$ by 5-6 MeV. This is attributed to the fact that the CMI of $\Delta\Delta_{(0,3)}$ is repulsive in contrast to that of $\Delta\Delta_{(3,0)}$, although their antisymmetrization characters are the same. The results with Sets 1 and 2 have small difference mainly because of the variation of g_q brought by the mass changes of κ and ϵ, although the strange meson clouds are not important in the non-strange system.

Then, we try to reveal the effects of chiral-quark interactions in $\Delta\Delta$ systems. This can be realized by locating calculations in other two chiral quark models, the extended $SU(2)$ and $SU(2)$ chiral quark models. In the former one (hereafter call Model II), the chiral-quark interactions are provided by scalar meson σ and all pseudoscalar mesons π, K, η and $\eta\prime$, while in the latter one (hereafter call Model III), the chiral-quark interactions are induced by the pseudoscalar meson π and scalar meson σ only. The results in these two models are also tabulated in Table 2. It is seen that the binding natures of the two systems remain the same, but the values of binding energies and RMS' have substantial differences. In the higher spin system like $\Delta\Delta_{(3,0)}$, the binding energy would increase when the model changes from I to II or III, and the largest value occurs in Model II. But in the lower spin state like $\Delta\Delta_{(0,3)}$, the binding energy changes in the opposite direction and the largest value appears in Model I. Anyway, the fact that the binding energy of the system with spin $S = 3$ is larger than that of the system with spin $S = 0$ remains un-changed when the model used is alternated.

Table 2 Binding energy B_{AB} and RMS for $\Delta\Delta_{(3,0)}$ and $\Delta\Delta_{(0,3)}$ systems†

Channel	one channel $\Delta\Delta_{(3,0)}$		one channel $\Delta\Delta_{(0,3)}$	
	$B_{\Delta\Delta_{(3,0)}}$ (MeV)	RMS (fm)	$B_{\Delta\Delta_{(0,3)}}$ (MeV)	RMS (fm)
Model I Set1	22.2	1.01	16.0	1.10
Model I Set2	18.5	1.05	13.5	1.14
Model II	64.8	0.84	6.3	1.25
Model III	62.7	0.86	13.2	1.11

† B_{AB} denotes the binding energy between A and B baryons and RMS represents the corresponding root-mean-square radius.

This result can be understood in the following way. The basic observation is that their symmetry structures, which cause $\langle\mathcal{A}\rangle^{sfc} = 2$, where sfc denotes that the operation takes place in the spin-flavor-color space only, is very beneficial in forming bound state. Namely, the quark exchange effect due to the Pauli principle is enormous so that the quarks in two clusters can be sufficiently close, and consequently the contribution from the kinetic energy term shows the attractive character. On the other hand, the σ field induced interaction

provides a fairly strong attraction which plays a dominant role in forming bound state. These two factors make the binding nature of the system stable with respect to models and parameters.

Moreover, from the form of Gell-Mann matrices we know that the K and κ meson exchanges do not exist between u or d quark pairs, namely the chiral fields K and κ do not contribute in both systems. The contributions from pseudoscalar mesons in two systems are comparable. But the contribution from the $\sigma\prime$ meson are characteristically different in these two systems. Opposite to the contributions of CMI, it is strongly repulsive in $\Delta\Delta_{(3,0)}$ and relatively weakly attractive in $\Delta\Delta_{(0,3)}$, and the repulsive strength of $\sigma\prime$ is much larger than the attractive strength in CMI. As a result, when one moves from Model I to Model II or III, the scalar mesons $\sigma\prime$, κ and ϵ are turned off, the wavefunction of $\Delta\Delta_{(3,0)}$ would move inward and that of $\Delta\Delta_{(0,3)}$ would distribute more outward. Consequently, the contribution from σ becomes stronger in $\Delta\Delta_{(3,0)}$ and a little weak in $\Delta\Delta_{(0,3)}$. That is why when model alternates from I to II or III, $\Delta\Delta_{(3,0)}$ becomes much more bounder and $\Delta\Delta_{(0,3)}$ turns out to be a little less bound.

Above results can be crosschecked by their S-wave scattering phase shifts and corresponding scattering lengths. We plot the S-wave phase shifts of these two systems in Figs. 1 and 2, respectively. The solid and dashed curves are those with parameter Sets 1 and 2, accordingly. With these phase shifts, one can easily extract the corresponding scattering lengths, which are tabulated in Table 4.

Table 4 The Scattering length a of the $\Delta\Delta$ systems

	one channel $\Delta\Delta_{(3,0)}$	one channel $\Delta\Delta_{(0,3)}$
Model I Set1	-1.30 (fm)	-2.56 (fm)
Model I Set2	-1.16 (fm)	-2.72 (fm)

Both phase shifts and scattering lengths are consistent with our above results.

4 Conclusions

In the $\Delta\Delta$ system, there exist two bound states, $\Delta\Delta_{(3,0)}$ and (d^*) $\Delta\Delta_{(0,3)}$. The former one has been predicted as a bound dibaryon [5,8-10]. Its binding energy varies model by model. By employing the $SU(3)$ chiral quark model with which the available empirical data can be well-reproduced, the binding energy of the one channel $\Delta\Delta_{(3,0)}$ (or d^*) is 18.5-22.2 MeV and the corresponding RMS is about 1.0 fm. This result is consistent with most reports of other

theoretical predictions [5,8-10]. Then, we predict the binding energy of $\Delta\Delta_{(0,3)}$. The result turns out to be 13.5-16.0 MeV and the corresponding RMS is around 1.1 fm. The binding behaviors of these systems are attributed to their special symmetry properties which make the contribution of kinetic energy term beneficial for forming dibaryons. Moreover, the chiral fields also provide substantial contributions to their binding behaviors. Among these chiral fields, the relatively stronger σ induced interaction is always the dominant one, no matter which model and model parameters are used. As a consequence, the binding phenomena of the $\Delta\Delta_{(3,0)}$ and $\Delta\Delta_{(0,3)}$ systems are always remained the same.

However, the mass of these two systems predicted in the one-channel approximation are all larger than the thresholds of strong decay channels $\Delta\Delta \to \Delta N\pi$ and $\Delta\Delta \to NN\pi\pi$ which are about 155 MeV and 310 MeV (even after considering the CC channel coupling in d^*, this conclusion is still true). These dibaryons would have very broad widths. Because the newly predicted $\Delta\Delta_{(0,3)}$ has the lower spin $S = 0$ with respect to $\Delta\Delta_{(3,0)}$, it might be more favorable to be experimentally detected.

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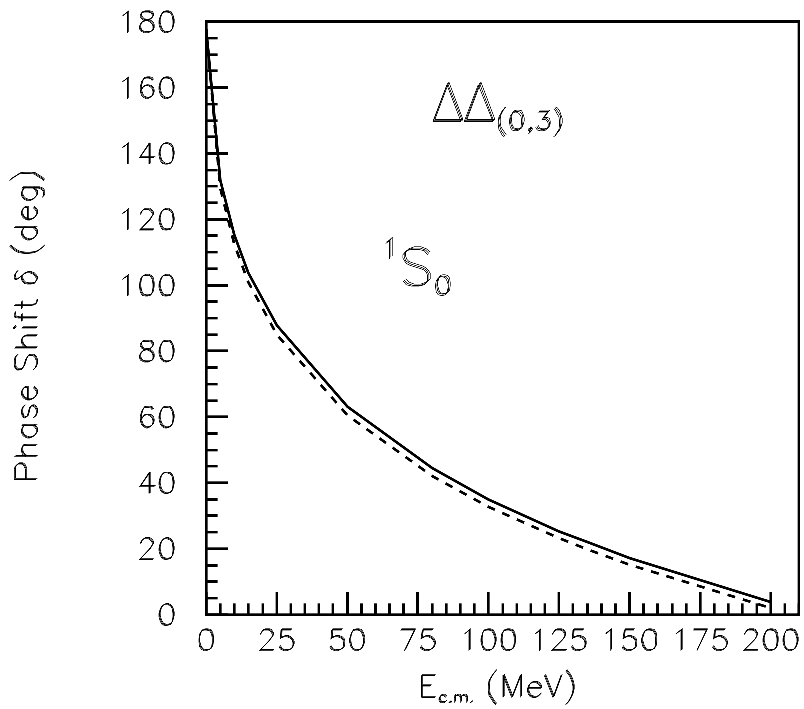

FIG.2. S-wave scattering phase shifts
for one channel $\Delta\Delta_{(0,3)}$.

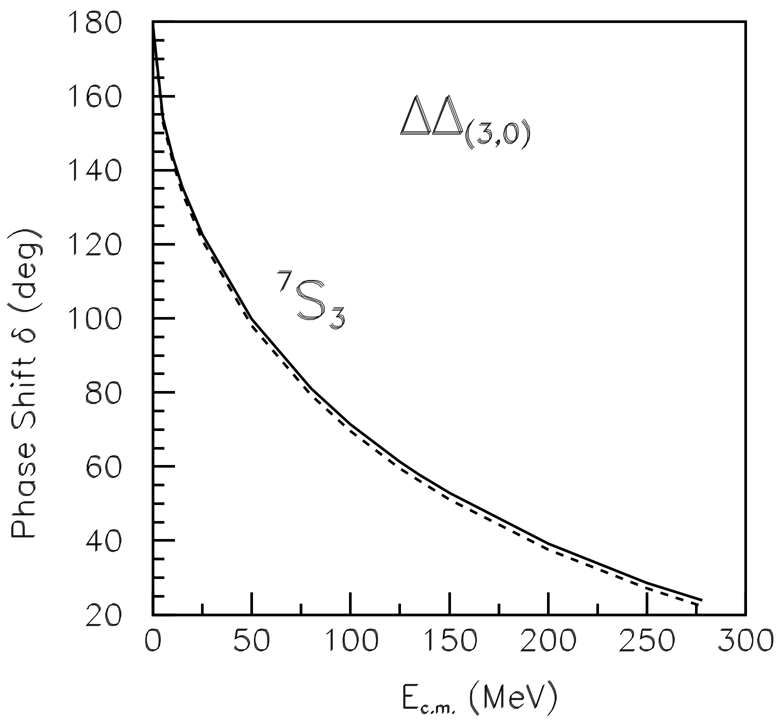

FIG.1. S−wave scattering phase shifts for one channel $\Delta\Delta_{(3,0)}$.